PERFORMANCE OF COMPACT AIR INSULATED SUBSTATIONS UNDER SURGE CONDITIONS

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Abstract: A number of options exist for reducing the footprint of substations using air-insulated switchgear (AIS). In this paper, a detailed model of an air insulated compact substation is developed, and overvoltage studies using EMTP are undertaken to evaluate the impact of compaction within the substation. One of the major practical aspects of compact substations is the performance of the substation under surge conditions. The lightning and switching overvoltages are calculated for a compact substation model, which is then compared with results obtained for a conventional substation layout. The results show that the extended use of surge arresters and a new approach to their location within the substation can lead to a significant reduction in the probability of overvoltage stresses to occur within the substation. This investigation demonstrates that air-insulated compact substations can be an attractive option for future substations.

1 INTRODUCTION

A number of options for reducing the footprint of substations using conventional air-insulated switchgear (AIS) have been investigated [1]. A compact AIS design would have advantages in applications where restrictions in the available land are encountered. For example, such a design might allow extension bays to be constructed within an existing substation boundary where space is restricted. Potential applications also arise where a replacement substation is to be constructed off-line on land adjacent to an existing substation, allowing the latter to remain in service during the construction period and avoiding the safety and operational issues associated with bay-by-bay replacement. Applications might also be found in urban areas. In such cases, a compact AIS substation might offer a cost-effective alternative to gas-insulated switchgear (GIS) substation and would reduce dependence on sulphur hexafluoride (SF_6), the use of which is being questioned on environmental grounds.

An important aspect of the feasibility of compact substations is the evaluation of its performance under surge conditions. Significant reductions in both air clearances between phases and in length of switch bays can lead to increasing surge reflections and phase-to-phase coupling. The effect of the presence of HV equipment needs also to be taken into account in order to estimate their influence on surge reduction. Furthermore, the introduction of new technology and new integrated equipment can lead to a different surge response of the substation.
In this paper, a detailed model of an air insulated compact substation is developed, and overvoltage studies using EMTP are undertaken to evaluate the impact of compaction within the substation.
In the initial investigation, the lightning surge performances of existing and compact substations are computed following a direct strike on a phase conductor of an incoming line.
This is then followed by switching surge studies in which the switching surge performances of the two substations are compared following a circuit breaker closure after fault clearance and an energisation of an incoming line. The effect of high-speed re-closure and circuit-breaker pole-scatter are also taken into account. Furthermore, simulations are performed to investigate the benefits of extended use of surge arresters.

2 EXISTING AND COMPACTION SUBSTATION OVERVIEW

UK current practice for air-insulated 400kV substations adopts a lightning impulse withstand voltage (LIWV) and a switching impulse withstand voltage (SIWV) of 1425kV and 1050kV respectively. These values represent the maximum values specified in IEC 60071 for a 400kV system voltage [2]. Consequently, the minimum phase-to-phase and phase-to-ground clearances, used by UK utilities in air insulated substation are 2850 mm and 3600mm respectively.

As presented in previous work [1], taking advantage of modern ZnO surge arresters, it is possible to reduce LIWV and SIWV to 1050kV/850 kV. In accordance with the specified IEC minimum values for this voltage level, it is possible to adopt the minimum phase-to-phase and phase-to-ground clearances of 2100mm / 2600 mm respectively.

A significant percentage of the substation footprint is occupied by conventional high voltage instrument transformers. Here, innovative fibre-optic transducers are selected for their small size and weight compared with conventional solutions. These new sensors can be integrated into circuit breakers and bushing, offering a nearly ‘zero foot print’ installations [3]. In existing transmission substations, voltage transformers (CVTs) and current transformers (CTs) are present at each line entrance, and their capacitances play a significant beneficial role in shaping and attenuating the transient surges impinging on the substation. In contrast, with the compact layout, current and voltage measurement devices which are based on fibre-optic sensors integrated around the circuit breakers have no such effect on surges.

The combination of compact clearances, non conventional instrument transformers and innovative high voltage equipment has resulted in a significant reduction of the substation footprint. Previous simulation results confirmed the feasibility of this compact layout although there was a lower margin for the compact arrangements.

In [4], novel non-horizontal bubsbar arrangements were proposed for compaction of AIS, and they were investigated for their electric and magnetic field magnitudes. These novel busbar arrangements are now introduced to allow further compaction of the substation layout. Therefore, it is essential to investigate their impact on the substation performances under lightning and switching surges.

Figure 1 shows the single line diagram of an existing 400/132kV substation adopted as a conventional layout. Three 400kV double circuit overhead lines feed the double busbar substation. The overhead lines consist of the following towers and lengths:

- L1 line is 100 km long and adopting L6 standard towers.
- L2 line is 40 km long and adopting L12 standard towers.
- L3 line is 40 km long and adopting L6 standard towers.

The phase conductors of L1 and L3 lines are 400mm^2 Zebra quad-bundled conductors and Redwood 850mm^2 twin conductors for L2 line. Two super-grid transformers interconnect the 400kV and 132kV systems; one at node 7 and the other at node 8. The 132kV voltage system was not taken into account.

3 EMTP SYSTEM MODELS

The selection of the EMTP models of network components adopted in this work follows the suggestions described in [5-9], and is briefly described below.

3.1 Feeding network

In the lightning model, any ac source voltage is neglected. For the switching model, a network short circuit power of 15GVA is assumed, which determined a short-circuit reactance. A parallel resistor is placed to set the equivalent surge-impedance of the network.

3.2 Overhead line model

The line sections and the spans are simulated using the JMarti model, a frequency dependent model with constant transformation matrix. Additionally, an alternative model is implemented using nominal PI-model at a selected frequency for comparison purposes.

The earthing electrodes of towers are represented by a linear resistance of 10Ω. The substation earthing meshed electrodes are neglected. Since each feeding line at the gantry presents inclined conductors to the connection to the busbar. In order to improve the simulation accuracy and avoid increased reflection due to the surge impedance difference between the overhead line and the busbars, the inclined conductors are modelled explicitly at an average height above ground [5].
Corona wave deformation is neglected since corona losses contribute to reduce the steepness of the lightning overvoltages over long distances, and this approximation is conservative.

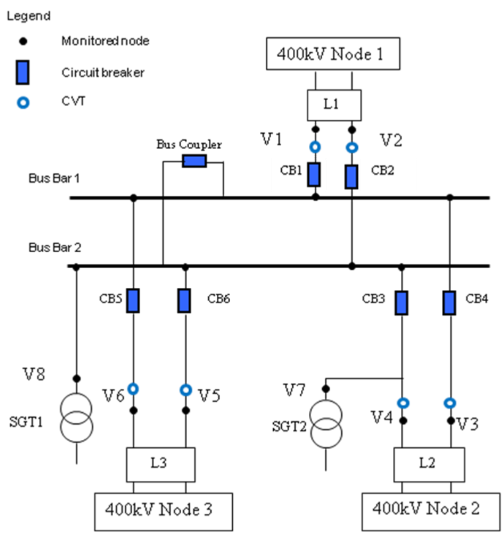

Figure 1 Single line diagram of the 400/132 kV substation.

3.3 Air insulated busbar model

The selection of the air insulated busbar model is not a trivial task. In fact, the busbar characteristics differ from those of the overhead line with its shorter finite length and lower conductor height above ground. Since the busbar length is extremely short, the minimum length considered is 10m in the two studied layouts. Several theoretical problems arise in applying a line model based on Carson’s equation for earth return, as described by Ametani in [6]. However, Watanabe et al. [9] analysed the surge characteristics using an AIS miniature model (scale 1:10) and compared the measurements with simulation analysis, and they found that the EMTP results of the various simulations agreed with experimental measurements when the multi-phase constant parameter model is used for lightning surge analysis in AIS.

For this reason, the un-transposed multi-phase constant parameter is adopted. Similarly, with the overhead line model selection, an alternative model is implemented using a nominal PI-model at a selected frequency for comparison purposes.

For the main and reserve busbars in the compact layout, the proposed vertical symmetrical arrangement is adopted. Figure 2 shows the heights of the busbar centres above ground for these proposed arrangements. Further information on dimensions of the busbar centres for all arrangements are detailed in [4].

In the conventional layout model, each busbar is introduced as separated line sections, connected only by the bus coupler and the incoming lines; with the two centres of busbars are 20m apart. In the compact layout, the two vertical symmetrical busbars have only 4.5m distance between the closest phase conductors; since the two busbars are supported by the same structure. The adoption of the multi-phase model permits to take into account the coupling between the two busbars, introduced as line sections with six phases.

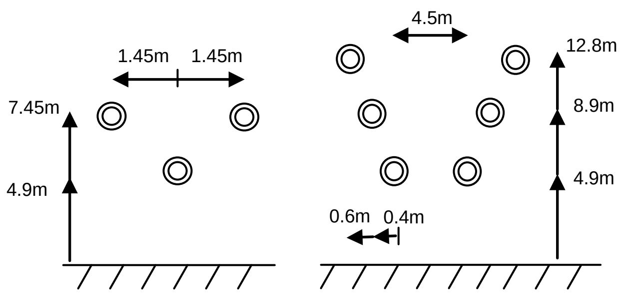

Figure 2 Proposed Delta and vertical busbar arrangements.

4 LIGHTNING SURGE PERFORMANCE

In the first investigation, the lightning surge performances of the existing and compact substations are computed. A direct stroke on the upper phase conductor is applied on an incoming overhead line. A shielding failure has a lower probability of occurrence than a back flashover but it gives a clear indication of maximum stress at the substation.

The shielding failure is located at 1.5 km from the substation. The lightning current is modelled as a 32kA current injected at the upper phase conductor. The lightning path impedance is modelled as a parallel resistance of 400 Ω to the current source similar to was described in the literature [4]. The possibility that a direct stroke could hit the substation is very low and, therefore, neglected in this work. Five spans of 300m length are accurately modelled between the lightning injection point and the substation. Furthermore, in addition to the five spans modelled from the injection point to the receiving end of the line, the remaining section at the line termination is simulated to avoid introducing incorrect reflections. For the studies, all three incoming lines are represented and connected to the substation. The regime of only one line feeding the substation is not considered since the very low probability of lightning striking under such rare operation conditions. As suggested in [8], a frequency of 500 kHz is selected for the constant-parameter calculations. The skin effect and the auto-bundle facilities were adopted.

The two substation transformers SGT1 and SGT2 are modelled as open circuit, since this is the worst condition for surge reflection. The presence of the super-grid transformers (SGTs) is taken into account by introducing a 3 nF capacitance to earth. Therefore, any overvoltages transferred to the lower voltage side of the transformer are not simulated. Similarly, the presence of capacitive voltage transformers (CVTs) in the conventional layout at each line entrance is taken into account by adding a capacitance to earth of 5 nF, which is the minimum value, as suggested in [7]. For the proposed compact substation, the CVTs are not present, since equipment using fiber-optic sensors (CTs and VTs) are now adopted.

The overvoltages within the substation are monitored at eight nodes, V1 to V6 at line entrances, V7 and V8 which are at the primary side of the SGTs, as shown in Figure 1. The pu values are computed adopting a voltage reference $U_{base} = \sqrt{2} \cdot U_m / \sqrt{3}$, where U_m is equal to 420 kV, highest system voltage. The highest overvoltages, for an existing and a compact substation at monitored nodes, following a stroke on line L1 and on phase-A conductor are shown in Table 1. Values exceeding LIWV values are underlined. The simulation results for existing and compact substations indicate that, at all eight monitored nodes, the selected LIVW values are exceeded. Due to surge reflections within the substation, the highest overvoltage is predicted at the HV side of the SGT.

Introducing ZnO surge arresters at each line entrance and on the HV side of both SGTs, the maximum overvoltages computed during the simulations are significantly reduced and, at all nodes, the maximum voltage values are below the

LIWV values. As expected, the residual margins to the LIWV values, expressed in percent in Table 1, are significantly higher than those for the compact layout. The minimum margin for the compact layout is equal to 12% at node V1.

An alternative model implemented using PI-model at a 500 kHz frequency is simulated for comparison purposes. This model shows conservative values in comparison with the model adopting the frequency-dependent model.

Further simulations are carried out to investigate the overvoltages due to a shielding failure on the other two transmission lines, L2 and L3. The results of the simulations showed similar results.

Table 1: Highest overvoltages at monitored nodes, stroke on line 1, phase A, for existing and a compact substations.

	Existing Substation LIWV 1425kV - 4.16pu			**Compact Substation** LIWV 1050kV - 3.06pu		
SAs	No	Yes	Marg.	No	Yes	Marg.
Nodes	pu	pu	%	pu	pu	%
L1-V1	5.84	2.73	34%	5.92	2.70	*12%*
L1-V2	5.84	2.54	39%	5.88	2.42	*21%*
L2-V3	5.48	2.62	37%	5.42	2.45	*20%*
L2-V4	5.39	2.63	37%	5.39	2.38	*22%*
L3-V5	5.78	3.02	27%	5.88	2.34	*24%*
L3-V6	5.78	2.86	31%	5.76	2.32	*24%*
SGT1-V7	5.57	2.49	40%	5.63	2.42	*21%*
SGT2-V8	5.91	2.44	41%	5.77	2.42	*21%*

Note: Values exceeding LIWV are underlined. Residual margin to the LIWV values indicated in percent.

5 SWITCHING SURGE PERFORMANCE

Another important evaluation in the feasibility study of the compact substation is the calculation of maximum voltages under slow front conditions. In this work, an operational regime is selected in which one circuit of each line is connected to the main busbar, while the other circuit of each line is connected to the reserve busbar. This regime may permit a higher level of system security by reducing the consequences of a failure of one section of busbar. Accordingly, this regime may represent a normal operating configuration.

Simulation studies are performed to calculate surges following typical events, such as line closure after fault and line energisation [10-11]. In addition, a high speed re-closure operation is simulated introducing trapped charges of +1p.u., -1p.u. and +1p.u. in the model. The decay of trapped charge present on the system under a re-closure switching event depends on the shunt conductance values of the busbar model and the presence of measurement transformers. Because the proposed compact substation design will have measurement devices based on fiber optic sensors; the charges remain longer in comparison of adoption of inductive type CTs and VTs. Therefore, they can play a significant role in peak overvoltages within the substation. In these studies, the leakage current on insulator surfaces and any associated pollution effects is neglected. A multi-phase model is adopted for busbar representation under switching conditions. JMarti model, representing line sections, requires a very low fitting frequency in presence of trapped charges as near DC frequency sources: a 0.0001Hz initial frequency is adopted.

In order to reduce the simulation time, the full sequence of switching actions that cause trapped charge is modelled; first opening of the circuit breaker followed by poles re-closures. The trapped charge is introduced in the isolated partial network as a current source, with a very low frequency 0.0001Hz and, then, a re-closure operation is performed. Using these special settings, the suggested trapped charges are injected in the system [12] and the sources are automatically disconnected at the first time-step.

It is well known that an important parameter of the overvoltage predictions is statistically dependent on the circuit-breaker pole scatter, which can lead to significant overvoltage variability. For insulation co-ordination purposes, a statistical switching study is usually adopted to calculate the cumulative density distributions of overvoltages. In this work a systematic approach was taken to explore all possible switching combinations for the compact substation model, which are then compared with results obtained for a conventional substation layout. Despite the fact that this method does not offer a fully realistic distribution of pole-closing combinations along the cycle, it allows to identify the worst combination of switching more directly. Using the EMTP systematic switching tool, a window of 120 degrees dividing into ten steps per phase is set up. The software then performs 1000 switching operations using the combination of all three pole-steps. A further series of simulations were performed with the inclusion of ZnO surge arresters.

The following two switching scenarios were investigated:

Scenario A: A closing operation at the substation entry point (L1), substation feeds from Line 1 (L1),

Scenario B: Energisation of a long line (L1), with the substation connected to the 400kV network from Lines 2 and 3,

For each scenario, after the initial simulations without SAs (Case1), the effect of fast re-closure

(Case2) was investigated and then a simulation of the worst case was performed with the introduction of surge arresters at the HV side of the SGTs, at line entrances and an additional SA at the bus coupler (the latter is for the compact layout only, Case 3).

Table 2 shows the calculated peak values of voltage at each node for the two switching scenarios and all cases studied for the conventional and compact substation models.

The analysis of the voltage distribution, resulting of the application of the circuit-breaker pole scatter for each case, is facilitated by a FORTRAN tool developed for this purpose. This tool helps to process the overvoltage data present in one of the ".lis" output files of EMTP, and to plot the distribution of peak overvoltages among selected nodes as shown in Figure 3.

Table 2: Maximum overvoltages within the substation for Scenarios A and B.

	Existing Substation SIWV 1050kV - 3.06pu		**Compact Substation** SIWV 850kV – 2.48pu	
Case	p.u	Marg.	p.u	Marg.
A.1	2.24	27%	2.40	3%
A.2	4.15	n.p.	4.32	n.p.
A.3	2.90	5%	2.17	12%
B.1	2.70	12%	2.68	n.p.
B.2	4.16	n.p.	4.40	n.p.
B.3	2.93	4%	2.05	17%

Note: substation not protected (n.p.).

It was found through this investigation that the highest overvoltage following a closing operation at the substation entry point (scenario A.1) is below the SIWV for both layouts. However, the margin for the compact substation is significantly lower, as expected. The presence of trapped charge (A.2) increases the overvoltages in both layouts over the SIWL; a consequent failure of equipment in the substation may be expected in this case. However, the introduction of metal-oxide surge arresters allows to reduce the overvoltages to within the SIWV for both layouts (A.3). It is worth noting that the compact layout benefits from an extra SA at the bus coupler.

Under scenario B, the energisation of line L1, the overvoltages computed at the monitored nodes shows that the absence of any overvoltage protection leads to the maximum voltage exceeding the LIWV for the compact substation (B.1). Further simulations under trapped charge conditions show very high voltage magnitudes within both substation layouts (B.2). Again, with the introduction of surge arresters, the LIWV condition is satisfied at all nodes (B.3) and for both configurations. Figures 3 and 4 show the switching overvoltage distribution at the substation nodes for conventional and compact substation layouts.

The simulations of these two scenarios demonstrates the feasibility of the proposed compact substation layout including the judicious selection of surge arresters locations at all line entries, at each SGT and at the bus coupler. A further beneficial effect could be achieved using point-of-wave switching or other techniques to reduce switching transients.

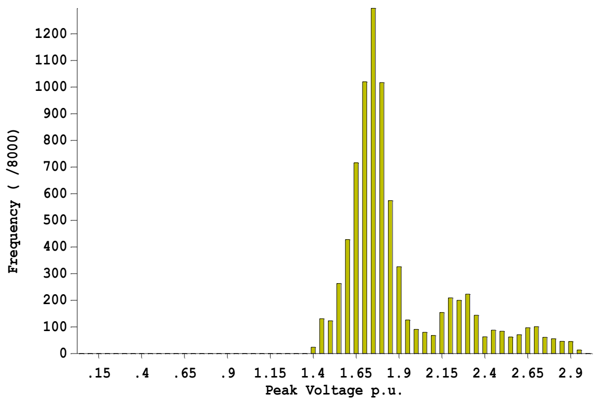

Figure 3 Switching overvoltage distribution at the substation nodes for conventional substation in presence of trapped charge and SAs (Scenario B.3).

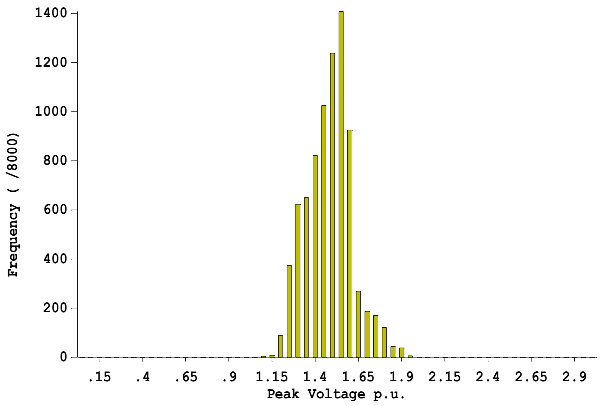

Figure 4 Switching overvoltage distribution at the substation nodes for compact substation in presence of trapped charge and SAs (Scenario B.3).

6 CONCLUSION

A detailed model of a proposed compact substation, adopting the IEC minimum clearances and alternative busbar arrangement, is investigated under lightning and switching surges. The computed results show good performance and acceptable margins under both lightning and switching overvoltage conditions. The careful selection of surge arrester locations at each incoming lines and within the substation, plays a fundamental role in these performances.

The significant footprint reduction that can be achieved with this new layout permits interesting applications in substation replacement and, in some cases, may offer an environmentally friendly alternative to existing gas-insulated switchgear option.

7 ACKNOWLEDGMENTS

The authors would like to thank National Grid for their financial support.

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